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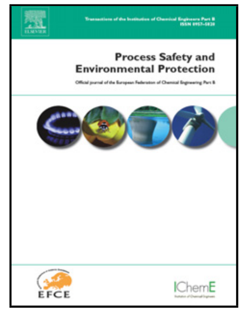
DOI 10.1016/j.psep.2017.10.019
ISSN 0957-5820
ESSN 1744-3598

Publisher: Elsevier

Accepted Manuscript



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PII:	S0957-5820(17)30373-7
DOI:	https://doi.org/10.1016/j.psep.2017.10.019
Reference:	PSEP 1216
To appear in:	*Process Safety and Environment Protection*
Received date:	23-7-2017
Revised date:	28-10-2017
Accepted date:	31-10-2017

Please cite this article as: Ifelebuegu, Augustine O., Awotu-Ukiri, Esiwo O., Theophilus, Stephen C., Arewa, Andrew O., Bassey, Enobong, The application of Bayesian – Layer of Protection Analysis method for risk assessment of critical subsea gas compression systems.Process Safety and Environment Protection https://doi.org/10.1016/j.psep.2017.10.019

The application of Bayesian – Layer of Protection Analysis method for risk assessment of critical subsea gas compression systems

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Highlights

- Bayesian-LOPA is proposed for use as risk analysis tool for SGCS
- Beyesian logic was used to update SGCS failure frequency data for LOPA application
- The tool provided a better and more reialable method for modelling event scenerios
- A better judgement can then be made in the application of SIS for a required SIL

Abstract:

Subsea gas compression system (SGCS) is a new critical subsea-to-shore field development solution that could reduce costs and environmental footprint. However, this system is not without inherent and operational risks. It is therefore, vital to evaluate the possible risks associated with SGCS to ensure the safe operation of the system. To this end, Layer of Protection Analysis (LOPA) is a suitable method for the estimation of possible risks. However, the failure rate data from SGCS required for LOPA is sparse and mostly developed from experimental testing. Bayesian (BL) logic is an effective tool that could be used to resolve this shortfall. In this paper, generic data from a secondary database was updated with SGCS specific data using BL logic to give a better risk frequency value. The key findings show that the posterior values derived from the BL-LOPA methodology are safer and more reliable to implement for an event scenario when compared to literature, expert judgement and generic data; therefore recommending an improved judgement in the application of safety instrumented systems for a required safety integrity level. The case studies used demonstrated that the BL-LOPA risk assessment method is sufficiently robust for quantifying uncertainties in new process facilities with sparse data.

Keywords: Bayesian; LOPA; Risk Assessment; Subsea Systems

Nomenclature

BL	Bayesian Logic
CCF	Common cause failure
CCPS	Centre for Chemical Process Safety
CM	Conditional modifiers
CPT	Conditional Probability Table
DAG	Directed Acyclic Graph
DNV-RP	Det Norske Veritas and Germanischer Lloyd
EC	Enabling Conditions
EIReDA	European Industry Reliability Data Bank
ESReDA	European Safety and Reliability Research and Development Association
ESDV	Emergency shutdown valve
ETA	Event Tree Analysis
FMEA	Failure mode and effect analysis
FTA	Fault Tree Analysis
HAZOP	Hazard and Operability Study
IE	Initiating Event
IEC	International Electro-Technical Commission
IPL	Independent protection layer
LOPA	Layer of protection analysis
MTBF	Mean time between failures
OREDA	Offshore reliability data
PAH	Pressure alarm
PCB	Pressure control valve
PFD	Probability of failure on demand
PHA	Preliminary Hazard Analysis
SGCS	Subsea gas compression system
SIF	Safety instrumented function
SIL	Safety integrity level
SIS	Safety instrumented system
A	An event A
A’	A not happening
B	An event B
E	An event E
n	Number of demands
t	Time
α	Beta distribution
β_{prior}	Non-informative prior
μ_{post}	Posterior distribution mean
γ_{prior}	Gamma distribution
p	Point of estimate

1. Introduction

The repercussions of recent oil and gas industrial accidents (for example Macondo) has brought various stakeholders back to the drawing board in order to limit the reoccurrence of such major events in the near future. Most of the current focus is on the drilling sector. In the near future, subsea systems will be brought under the scrutiny of both the public and regulators for review under any of the process safety and resource management service institutions [1]. Most exploration and production companies that deal with subsea operations and legislative bodies have effectively the required standards on what systems and strategies must be put in place to ensure effective risk management [2]. These standards in themselves

however are insufficient to control and minimise risks and can be considered only as part of the integrity management lifecycle [3]. Subsea systems which are comprised mainly of flow-lines, production risers and subsea trees etc. located on the seabed will become an obvious target for redundancy requirements, fail-safe or reliability demands, similar to those obtainable in other industrial processes.
The issues of fines and penalties for failure will also come into play as a measure to ensure subsea systems are protected. Technically, the subsea gas compression system (SGCS) component in this paper is mainly considered as a critical unit operation in subsea systems. While this is the case, the same principles of risk management can be replicated for any unit operation found in a subsea system. This technique is highly efficient because it generally pushes the gas rather than sucks it up to the surface [4]. Substantial efforts are made during the construction phase of the SGCS. It goes through various stages from qualification down to operational, which comprises the assessing and determination of the environmental conditions (deep sea) that will later become the work environment of the installed SGCS [5]. The elementary variables included are the conditions of the top of the seabed, the sea surface current, wave impacts, the composition of the seabed soil settings, the topography, geographic location and firmness, etc. Other elements such as the type of fluid, the selection of materials, the mitigation of corrosion, interaction from third parties, design and life etc. are all areas that can be examined for risk assessment.

According to Bai and Bai [6], risk assessment is a significant part of project management in industrial fields. It helps in the identification of risks in the operating process of a system. Reliability risk analysis must be applied throughout the various sections of a system operation process. The quantification of a system's probability of failures and the consequent effects of such failures are conveyed under risk assessments. This makes the analysis of failure modes and mechanisms a necessary procedure, particularly at the commencement of a process design when actions can easily be corrected and implemented. The analysis of failure came about due to the need to troubleshoot and also the need to solve reactive problems. In the international community, there are various techniques and methodologies used for risk assessment including: Fault Tree Analysis (FTA), Preliminary Hazard Analysis (PHA), Event Tree Analysis (ETA), Cause-Consequences Analysis, Failure Modes and Effects Analysis (FMEA), Relative Ranking, Checklists, Safety Review, What-If Analysis, Hazard and Operability Analysis (HAZOP) and Layer of Protection Analysis (LOPA) [7]. The purpose of these techniques is to ascertain and prevent design or process malfunctions, to ensure the reliability of the process lifecycle duration and the general protection of the process to avoid hazards while in operation.

1.1. Layer of Protection Analysis (LOPA)

LOPA is a risk management technique commonly used in the chemical process industry that can provide a more detailed, semi-quantitative assessment of the risks and layers of protection associated with hazard scenarios [8, 9]. The LOPA method enables users to determine risks associated with hazardous events through the severity and the likelihood of such events occurring. With the aid of cooperative or international risk standards, LOPA users can ascertain the maximum amount of risk reduction necessary through analysing the various layers of protection [10]. If an additional risk reduction layer is required in addition to that given by the system design, other actions are taken into consideration, namely the basic process control system, pressure relief valves, alarms and related operator actions among others. This could then require a safety instrumented function (SIF) or safety instrumented system (SIS). The safety integrity level (SIL) of the safety instrumented function can be ascertained directly from the additional risk reduction required [11]. Jin *et al.* (2016) [12] discussed the theoretical basis of quantification for LOPA by comparing the computing methods of event tree consequences. The values obtained from LOPA can then be recorded as variables which can be computed for a Bayesian network, thereby critically analysing LOPA's limitations.

1.2. Bayesian Logic (BL)

Bayesian logic is a directed acyclic graph (DAG) defined by a set of nodes and sets of directed arcs. The nodes denote the variables of a process and the arcs denote the dependencies or the cause and effect associations between them [13]. Each node state is related to probabilities. The probability is measured through deductive reasoning for a parent/root node which is then computed into the BL by inference for other sub nodes. Each sub node has a supplementary probability table named the conditional probability table (CPT) [14]. The computation of the logic is conducted via the Bayes theorem which states that if Pr(E) is the probability of E happening, then P (A/E) is the probability of A happening given that E has happened, given that Pr(E) is not equal to zero. The most common form of Bayes equation is

$$P(A|E) = \frac{Pr(E|A) \times P(A)}{Pr(E)} \qquad (1)$$

where

$$\mathrm{P(E)} = \mathrm{P(E|A)} \times P(A) + P\ (E|A') * P(A') \qquad (2)$$

A' = A not happening

The right-hand side of Equation 1 denotes the initial condition. After it is computed, the left-hand side known as the posterior values will be given [15]. The value of P(A) is the initial probability and Pr(E|A) is the likelihood function, which is a data specific situation. Pr(E) is the probability of E which is calculated from equation 2. This paper provides research into the process hazard analysis of a subsea gas compression system by modelling the estimated risk levels to be acquired over a period. The data obtained is updated using Bayesian logic. The derived values are then used to model an event scenario with independent protection layers including common cause failure and any other uncertainties in a subsea gas compression system. The results from the model are analysed using LOPA. This use of Bayesian-LOPA methodology for the risk estimation of subsea gas compression systems with limited and sparse operational data is new. The main aim of this paper therefore is to demonstrate the robustness of the Bayesian-LOPA risk assessment methodology in quantifying uncertainties in new subsea gas compression systems.

2. Methodology

2.1 Failure Frequency Data Sources

Bayesian logic requires the availability of failure frequency data, generic and SGCS (likelihood) data. This paper uses data from various sources ranging from historical data for SGCS components from organisations or research papers, to commercial and governmental handbooks of failure rate data. Brief explanations of these sources are given in Table 1 below:

2.2 SGCS Case Study

This paper concentrates on the typical design development type for subsea gas compression. The world's first SGCS (Asgard SGCS) unit operation specifications will be used as a case study for the development of the event scenarios operation. In September 2015, Asgard SGCS (Aker Solutions) became the first SGCS to commence operation. The components and design specifications are shown in Table 2. Three case scenarios were used (see Table 7). Case 1 deals with a human error initiating event with no prior information given, case 2 deals with an external initiating event with the prior information given, case 3 deals with equipment failure while case 4 is a combination of the initiating events and IPLs of the three case scenarios earlier described.

2.3 Bayesian Logic Evaluations

2.3.1 Bayesian Logic Evaluation for Initiating Events

Initiating event frequencies are estimated using BL. The conjugate prior distribution is used as the gamma distribution and the likelihood function is the Poisson distribution. The conjugate model of gamma distribution is used to obtain the posterior data of failure frequency. The posterior distribution uses OREDA data obtained from gamma distribution. SGCS failure frequencies derived from previous database of mainly topside facilities are used as likelihood functions in the Poisson distribution. Bayesian logic estimates the newly developed posterior failure frequencies of initiating events. This is the concept behind generating conjugate distribution values based on Bayesian estimation. Where values differ in the Bayesian estimate of the gamma distribution formula as in the case of OREDA, Equation 3 can be rewritten as equation 2 to adapt the OREDA database gamma distribution.

$$f(\lambda) = \frac{\beta^{\alpha}}{\Gamma(\alpha)} \lambda^{\alpha-1} e^{-\lambda\beta} \qquad (3)$$

$$f(\lambda) = \frac{1}{\gamma^{\alpha}\Gamma(\alpha)} \lambda^{\alpha-1} e^{-\frac{\lambda}{\gamma}} = \frac{(\frac{1}{\gamma})^{\alpha}}{\Gamma(\alpha)} \lambda^{\alpha-1} e^{-(\frac{1}{\gamma})\lambda} \qquad (4)$$

Examining equations 3 and equation 4, a variance is observed in a parameter which has the relation

$$\beta = \frac{1}{\gamma} \qquad (5)$$

With the substitution of equation 5, a new equation of posterior values emerges as

$$\alpha_{post} = x + \alpha_{prior}, \qquad \beta_{post} = t + \beta_{prior} = t + 1/\gamma_{prior} \qquad (6)$$

Where the posterior distribution mean frequency is:

$$\mu_{post} = \frac{\alpha_{post}}{\beta_{post}} = \frac{x + \alpha_{prior}}{t + \beta_{prior}} = \frac{x + \alpha_{prior}}{t + 1/\gamma_{prior}} \qquad (7)$$

In occasions where there is little or no generic data for some devices, the Jeffrey's non-informative prior is used. The Jeffrey's non-informative prior and posterior means are represented by Equation 8 and 9 respectively.

$$\alpha_{post} = x + 0.5, \qquad \beta_{post} = t \qquad (8)$$

$$\mu_{post} = \frac{\alpha_{post}}{\beta_{post}} = \frac{x + 0.5}{t} \qquad (9)$$

2.3.2 Bayesian Logic Evaluation for independent protection layers (IPLs)

PFDs of IPLs are estimated using BL. For the conjugate prior, beta distribution is used while the likelihood function uses the binomial distribution. The conjugate concept is used to obtain the PFD posterior data via binomial distribution. The data obtained from the various databases is directly used for PFD beta distribution [27]. The frequency PFD conversion method is used where the values of α and β of PFD are missing for some devices in a database. For example, OREDA and SGCS data failure frequencies are used where available as the likelihood function of binomial distribution. Conversely, if the number of demands for SGCS failure frequency is unavailable, an estimated correlation is made using the PFD estimating and point estimate equations. When this is achieved, the new IPL posterior PFD is estimated by Bayesian logic via beta distribution. Assuming that the period starting time t is not dependent on the probability and that during standby periods system failures are independent of each other, then the probability of a system failure observed at time t is:

$$p = 1 - e^{-\lambda t} \qquad (10)$$

The failure frequency is λ [28]. For a failure occurring during an assumed periodic device test, the PFD can be approximately estimated when detected during the test by:

$$PFD = \frac{\lambda T_{test}}{2} \qquad (11)$$

The test interval is λT_{test}. A table showing the test intervals of some devices is generated and used in case scenarios as required. As explained in section 2.5.4 above, the point estimate p is used for the frequency estimates.

$$p = x/n \qquad (12)$$

The mean time interval between two failures (MTBF) when λ is assumed to be constant is [29]:

$$MTBF = \frac{1}{\lambda} \qquad (13)$$

If the values of equation 11 and 12 are assumed to be the same then the correlation of equations 11, 12 and 13 gives the number of demands equation as:

$$n = \frac{2x}{\lambda T_{test}} = \frac{2xMTBF}{T_{test}} \qquad (14)$$

Using Equation 14 above, the number of failures, the number of demands, the test interval and the MTBF of an operation is estimated. Therefore, the PFD posterior mean can be calculated with the equation. When a database does not give the failure frequency data for some devices, OREDA is used. The necessary conversion of the frequency into PFD is due to OREDA being in gamma distribution. This needs to be adapted for beta distribution. Occurrences ranging from 0 to 1 can be modelled by beta distribution due to its flexibility [30, 31]. If the probability range is from 0 to 1, then it can be assumed that the PFD intervals are in line with the beta distribution. This means that the mean, upper and lower % of credible interval PFD values follow the beta distribution. α and β are the two values of beta distribution and the mean value is given by equation 15.

$$\mu = \frac{\alpha}{\alpha + \beta} \tag{15}$$

Making β the subject equation, 16 is obtained

$$\beta = \frac{\alpha(1-\mu)}{\mu} \tag{16}$$

Describing α and μ with the three factors consisting of the 5% credible lower PFD value, α and β values, then the value of α is:

$$Betadist(PFD_L, \alpha, \alpha(1-\mu)/\mu) - 0.05 = 0 \tag{17}$$

Betadist is the cumulative beta probability density function. The unknown variable in the equation 17 above is α and a Microsoft Excel spread sheet is used to obtain the value. The value of β in equation 16 above is found after obtaining the value of α and μ. These values are used for the prior information of beta distribution in Bayesian logic. The steps taken for the posterior distribution and likelihood function evaluation by Bayesian logic is observed in the same way as the other database prior distribution. The use of Jeffrey's non-informative prior distribution is used when there is little or no information from the prior distribution or generic data of a given device [32]. The relationship between beta distribution and Jeffrey's non-informative prior α and $\beta = 0.5$ therefore the following equations are used.

$$\alpha_{post} = x + 0.5, \qquad \beta_{post} = n - x + 0.5 \tag{18}$$

$$\mu_{post} = \frac{\alpha_{post}}{\alpha_{post} + \beta_{post}} = \frac{x + 0.5}{n + 1} \tag{19}$$

Other steps remain constant for situations in which there is informative prior.

2.4 Common Cause Failure Effects for Multiple Devices

The failure of a device or the occurrence of an event which causes the failure of an entire system is known as common cause failure (CCF) [33, 34]. There are different ways of modelling CCFs which can be classified under two methods, namely explicit and implicit. The explicit method is used when the dependency failure causes are known, for example environmental events or human error etc. This involves the addition of a dependency cause value into a given analysis [35]. According to Hauge *et al.* [36], dependent failure causes are in most cases difficult or impossible to determine through the explicit method. Therefore, the implicit method is used for dependency failure causes. Examples of the implicit method are multiple Greek letters and the alpha and beta factor. The latter has gained wide acceptance in the process industry and is used to calculate the PFD effect of CCF [23]. Process industries install multiple devices to reduce the frequency or probability of failure. Two methods used in the process industry include the 'one out of two devices works' (1002) and the 'two out of three devices work' (2003).

Method one's PFD average is

$$PFD = (PFD_{1oo1})^2 + \left(\frac{\beta\lambda T_{test}}{2} + \beta\lambda MTTR\right) \qquad (20)$$

Assuming $MTTR \lll T_{test}$, then $\left(\frac{\beta\lambda T_{test}}{2} + \beta\lambda MTTR\right) = 0$, this is realistic because repair time is a lot less than the test interval, therefore equation 20 can be rewritten as:

$$PFD = (PFD_{1oo1})^2 + \left(\frac{\beta\lambda T_{test}}{2}\right) = (PFD_{1oo1})^2 + \beta(PFD_{1oo1}) \qquad (21)$$

$\beta(PFD_{1oo1})$ is the effect of Common Cause Failure β derived from expert judgement.

Method two's PFD average is:

$$PFD = 3(PFD_{1oo1})^2 + \left(\frac{\beta\lambda T_{test}}{2}\right) = 3(PFD_{1oo1})^2 + \beta(PFD_{1oo1}) \qquad (22)$$

2.5 Bayesian-LOPA Work Sheet and SIL Determination

The Initiating events and PFDs of IPLs are obtained from the various database sources described above in section 2.1. For a particular event scenario, a customised database table is prepared and referenced where appropriate. The values for each event scenario developed from the customised tables are input into the Microsoft Excel spread sheet. The values for the frequency of an event scenario (prior, likelihood and posterior) are generated automatically as the required data is keyed into a Microsoft Excel spread sheet. The mitigated consequence from Bayesian logic is solved with equation 23 and 24 and written in a LOPA work sheet, then compared with the tolerable risk criteria [37]. Mitigated consequences without SIS are derived by adding the initiating events to the various IPLs for a particular event scenario using equations 25 and 26 for SIL determination. The SIL is derived using equation 27 below and the result is compared with Table 3 below to obtain both their level of risk and the risk reduction required. Each level of risk in Table 3 is obtained within a range of values of system integrity levels (SIL). If the SIL is not up to the tolerable risk criteria, another instrumented system is added to it until an appropriate SIL is achieved. Generally, the higher the SIL the more expensive is the system. Figure 1 below shows a summary of the above methodology. Table 4 below shows the tolerable frequencies given to each category which encompasses human, environmental and process system safety. Values vary from country to country and depending on the nature of the loss, various industries provide average criteria to be used for their calculations and the value range of 1.0×10^{-3} to 1.0×10^{-5}, a guideline by CCPS, is used. In this paper however, the tolerable frequency used is 1.0×10^{-5}. This is more suitable for a process system and its environment, as it is completely automated and operates in the sea. The target frequencies are for single scenarios with multiple initiators. Figure 1 describes the flow diagram of this research work adapted from Yun [31].

$$\text{mitigated consequence} = IE \times \prod_{j=1}^{J} PFD_j \qquad (23)$$

$$\text{mitigated consequence} = IE \times EC \times CM \times \prod_{j=1}^{J} PFD_j \qquad (24)$$

$$\text{mitigated consequence without SIS} = IE + \sum_{j=1}^{J} PFD_j \qquad (25)$$

$$\text{mitigated consequence without SIS} = IE \times EC \times CM + \sum_{j=1}^{J} PFD_j \qquad (26)$$

$$\text{SIL} = \frac{Tolerable\ Frequency}{Mitigated\ Consequence(without\ SIS)} \qquad (27)$$

3 Results and Discussions

3.1 Event Scenario Development

Three event scenarios are developed and analysed, then their worst consequences are considered. The refining of the PFDs for the IEs and IPLs with BL then produces a new LOPA sheet with recommendations made by the addition of a new SIS if the IPLs do not reach the SIL [31, 39]. Case 1 and Case 2 event scenarios use the same unit operation, namely a separator; but Case 1 is assumed to have prior information with the initiating event being that of an external influence while Case 2 is assumed to have no prior information with the initiating event being that of human error. Case 3 considers a different unit operation, in this case a multiphase pump and the initiating event is assumed to be caused by equipment failure. These three scenarios therefore cover the three major causes of an incident in the operating process of a system and consider the SIL for the initiating event, before implementing the IPLs. Case 4 on the other hand provides a combination of initiating events and some IPLs of the three event scenarios to show the effects of CCF and other external conditions. The progression in Case 4 is shown through a LOPA event tree. The values used are drawn from the customised table shown below. Figure 2 below shows the gas liquid separator

3.2 Customised Tables

Keyword similarities between FEMA and HAZOP mapped into LOPA are as follows: Guideword or severity, Layers of Protections or risk reducing measure, deviation or failure mode. These are shown in Table 5 below while only the causes and consequences are given in table 6, thereby mapping the critical information from HAZOP into LOPA.

3.3 Case 1

The following event scenario is assumed to be high risk, as overpressure of the separator leads to a loss of containment into the marine environment, causing pollution. The increase in the separator's pressure is due to a pressure surge from the reservoir detailed in the customised Table 5. Tables 7 and 8 show the values used in the calculations. The considered IPLs are pressure alarm (PAH), pressure control valve (PCV) and an emergency shutdown valve (ESDV) termed IPL1, IPL2 and IPL3 respectively. Figure 2 above provides an overview of the IPLs and where they are positioned. The initiating event frequency can be attained from OREDA and a subsea database. After inputting the prior and likelihood values into the Excel sheet, the posterior value from the Bayesian logic calculation was solved to be 6.7×10^{-2}. Figure 3a shows the posterior value to be between the prior and likelihood values.

IPL1 is estimated using Bayesian logic and the calculated PFD is 2.4×10^{-1}. From Figure 3b, it is observed that the posterior value is greater than the prior and likelihood values, thus showing that the values from the database were updated. The failure frequency was provided by OREDA giving the upper, lower and standard deviation values. These were converted with the PFD converter to find the alpha and beta values. IPL 2 gave a value of 5.0×10^{-4} as shown in Figure 3c and the prior and likelihood values were acquired from EIReDA and CCPS. They had alpha and beta values and needed no conversion. IPL3 gave a posterior value of 5.8×10^{-3} as shown in Figure 3d and the prior and likelihood values were acquired from EIReDA and CCPS. Again, they had alpha and beta values and needed no conversion.

Considering the event scenario described above, the mitigated frequency is the product of all the posterior values of the initiating event and the three IPLs. This gives:

$$\text{mitigated consequence} = 6.7 \times 10^{-2} \times 2.4 \times 10^{-1} \times 5.0 \times 10^{-4} \times\ 5.8 \times 10^{-3}$$
$$= 4.5 \times 10^{-8}$$

$$\text{mitigated consequence without SIS} = 6.7 \times 10^{-2} + 2.4 \times 10^{-1} + 5.0 \times 10^{-4} +\ 5.8 \times 10^{-3}$$
$$= 3.1 \times 10^{-1}$$

$$\text{SIL} = \frac{1.0\times10^{-5}}{3.1\times10^{-1}} =\ 3.2 \times 10^{-5}$$

From Table 3 it can be seen that the mitigated consequence is lesser than the tolerable risk criteria, while the value calculated from the SIL calculation above shows there is no need to consider a new SIS because the mitigated consequence value shows that the risk has been reduced. The mitigated frequency of Case 1 is evaluated with a LOPA sheet shown in Table 9 below.

3.4 Case 2

The event scenario is assumed to be high risk as overpressure of the separator leads to a loss of containment into the marine environment causing pollution. This is similar to Case 1 except that human error is considered as the initiating event. The operator is assumed to ignore the increase in pressure in the separator thereby failing to alert the system to balance out the threat by activating an IPL (e.g. pressure alarm). Tables 7 and 8 show the values used in the Excel calculations. The likelihood value for human error is based on both expert judgement and CCPS. The considered IPLs also remain the same as in Case 1. The initiating event frequency for human error is calculated with the Jeffery's non-informative prior due to a lack of prior information from the generic database as described in section 2.5.4. Therefore, only likelihood and posterior values were obtained in the Excel worksheet. The posterior value from the Bayesian logic calculation was solved to be 5.0×10^{-2}. Figure 4 shows the updated Bayesian logic posterior value compared to the likelihood value per year. The values of the IPLs remain the same as those in Case 1. Considering the case scenario described above, the mitigated consequence is the product of all the posterior values of the initiating event and the three IPLs. This gives:

$$\text{mitigated consequence} = 5.0 \times 10^{-2} \times 2.4 \times 10^{-1} \times 5.0 \times 10^{-4} \times\ 5.8 \times 10^{-3}$$
$$= 3.4 \times 10^{-8}$$

$$\text{mitigated consequence without SIS} = 5.0 \times 10^{-2} + 2.4 \times 10^{-1} + 5.0 \times 10^{-4} +\ 5.8 \times 10^{-3}$$
$$= 3.0 \times 10^{-1}$$

$$\text{SIL} = \frac{1.0 \times 10^{-5}}{3.0 \times 10^{-1}}$$
$$=\ 3.3 \times 10^{-5}$$

Again, the mitigated consequence is lesser than the tolerable risk criteria, while the value acquired from the SIL calculation above shows there is no need to consider a new SIS because the mitigated consequence value shows that the risk has been reduced. The mitigated frequency of Case 2 is evaluated with a LOPA sheet shown in Table 10 below.

3.5 Case 3

The event scenario is assumed to be of high risk in that equipment failure of a multiphase pump causes damage to the SGCS leading to increased maintenance costs. The customised Tables 7 and 8 show the values used in the Excel calculations. The considered IPLs are as follows: a detector and an alarm (IPL1), a backup pump (IPL2) and an emergency shutdown valve (ESDV) (IPL3). The initiating event frequency is obtained from OREDA and the subsea data likelihood was obtained from Dash (2012). After inputting the prior and likelihood values into the Excel sheet, the posterior value from the Bayesian logic calculation was solved to be 3.8×10^{-1}. Figure 5a below shows the posterior value to be in between the prior and likelihood values. The calculated posterior values for the detector and backup pump are 3.0×10^{-4} respectively.

IPL1 consists of a level detector and an alarm. The calculated posterior value for the detector from the excel spread sheet is 6.4×10^{-2} Figure 5b below shows the posterior value of the level detector compared to the prior and likelihood values. If it is assumed that the level detector and the alarm are independent of each other, thus the Boolean equation below can be used to find the PFD of IPL1.

$$\Pr(A \cup B) = \Pr(A) + \Pr(B) - \Pr(A) \times \Pr(B)$$

Where $\Pr(A \cup B)$ is the PFD of IPL1, Pr(A) is the PFD of the level detector and Pr(B) is the PFD of the alarm, using the PFD posterior value 2.4×10^{-2} of the alarm in Case 1; therefore:

$$\mathrm{IPL1} = \Pr(0.0635 + 0.2349) - \Pr(0.0635 \times\ 0.2349)$$
$$IPL1 = 2.8 \times 10^{-1}$$

IPL2, which is the backup pump, gave a posterior value of 3.0×10^{-4} as shown in Figure 5d below. The prior and likelihood values were derived from EIReDA and Dash's research respectively. It had alpha and beta values and needed no conversion. IPL3 is the emergency shutdown valve. The PFD posterior value 5.8×10^{-3} of Case 1 is used. Considering the case scenario described above, the mitigated consequences are the product of all the PFD posterior values of the initiating event and the three IPLs. This gives:

$$\text{mitigated consequence} = 3.8 \times 10^{-1} \times 2.8 \times 10^{-1} \times 3.0 \times 10^{-4} \times\ 5.8 \times 10^{-3}$$
$$= 1.9 \times 10^{-7}$$

$$\text{mitigated consequence without SIS} = 3.8 \times 10^{-1} + 2.8 \times 10^{-1} + 3.0 \times 10^{-4} +\ 5.8 \times 10^{-3}$$
$$= 6.7 \times 10^{-1}$$

$$\mathrm{SIL} = \frac{1.0 \times 10^{-5}}{6.7 \times 10^{-1}}$$
$$=\ 1.5 \times 10^{-5}$$

The mitigated consequence is less than the tolerable risk criteria. Looking at Table 5, the mitigated consequence value shows that the risk has been reduced. However, the value derived from the SIL calculation above shows there is a need to consider a new SIS because the SIL value falls under category 4 in Table 5. The mitigated consequence of Case 3 is evaluated with a LOPA sheet shown in Table 11 below.

3.6 Case 4

This event scenario is intended to explain the implications of modifying an initiating event by including enabling conditions (EC), conditional modifiers (CM) and also the effects of common cause failure (CCF) using method one, as explained in section 3.5. Figure 6 shows a LOPA event diagram illustrating the event procedure. The initiating events of Cases 1, 2 and 3 are the respective values of IE, EC, and CM while the considered IPLs are as follows. IPL1 consists of two high level alarms, if they are connected to the same system procedure. The CCF of the IPL therefore is found by assuming that the beta factor is 5% from expert judgements while the PFD of the alarm in Case 1 is used as PFD_{1oo1} to get PFD_{1oo2}. IPL2 is the operator response and is assumed to be perfect, so the PFD value is 1. IPL3 is assumed to be the ESDV with the value of 5.8×10^{-3}, thus the PFD value for IPL1 will be:

$$PFD_{1oo2} = (PFD_{1oo1})^2 + \beta(PFD_{1oo1})$$

$$PFD_{1oo2} = (2.4 \times 10^{-1})^2 + 0.05(2.4 \times 10^{-1})$$

$$PFD_{1oo2} = 0.0576 + 0.012$$

$$PFD_{1oo2} = 6.7 \times 10^{-2}$$

$$\therefore\ IE = 6.7 \times 10^{-2}, EC = 3.8 \times 10^{-2}\ and\ CM = 5.0 \times 10^{-2}.$$

$$\text{mitigated consequence} = IE \times EC \times CM \times \prod_{j=1}^{J} PFD_j$$

$$\text{mitigated consequence} = 6.7 \times 10^{-2} \cdot 3.8 \times 10^{-2} \cdot 5.0 \times 10^{-2} \cdot 6.7 \times 10^{-2} \cdot 1.0 \cdot 5.8 \times 10^{-3} = 4.9 \times 10^{-8}$$

Therefore, the mitigated consequence is lesser than the tolerable risk criteria, as seen in Table 5. With respect to the implementation of a SIS, it is assumed that the system has failed although the IPLs all functioned properly. If this is the case, the PFDs of the three IPLs have the value of 1, thus:

$$\text{mitigated consequence without SIS} = (6.7 \times 10^{-2} \cdot 3.8 \times 10^{-2} \cdot 5.0 \times 10^{-2}) = 2.7 \times 10^{-4}$$

$$\text{SIL} = \frac{1.0 \times 10^{-5}}{2.7 \times 10^{-4}} = 3.7 \times 10^{-2}$$

The value derived from the SIL calculation above shows that there is a need to consider a new SIS to reduce the risk because the SIL value falls under category 2 in Table 5.

3.7 Results Validation and Limitations

The posterior values are derived using Bayesian logic. For solving likelihood and prior information, the posterior data should be in-between the likelihood and prior information for the event scenarios where there is informative prior. A good example is figure 5c of Case 3 which shows that the frequency of pump failure was successfully updated with Bayesian logic. From the calculations, some of the posterior values did not meet this criterion. This means that either obsolete data was used or the likelihood information, which should be from a SGCS, was not accurate. This is so because SGCS is a new technology whereby the only data that can be obtained are experimental and not from long term operations due to its novelty. Nonetheless, the use of other plant and research information related to the SGCS is a welcome step in reducing uncertainties and also helps in modelling values for risk assessments. On this basis, a verdict can be given in favour of the approach taken if more reliable data could be accessible. However, the validity is not always true for the final PFD values of an event scenario evaluated with LOPA. The values are either obtained by multiplying the initiating event with the IPLs or by adding the Initiating event to the IPLs if it can be proven that the IPLs' PFDs values are gained without a SIS. The equations 23, 24, 25, 26 and 27 in section 3 were used to explain this. In some cases, expert judgement had to be used. To achieve the requirement of LOPA for an IPL, Boolean algebra was introduced for protection layers that might not reach these requirements but whether this strengthened or weakened the values obtained is beyond the scope of this paper. There was difficulty in modelling an event which would have required a SIL implementation due to sparse data with regard to SGCS, as previously discussed in section 2. The unit operations were assumed to function throughout the entire operating time of the Asgard SGCS [41]. This may have caused some discrepancies in the values of the PFDs. Generally, the experience of a process industry is vital in the completion and successful application of LOPA.

4 Summary and Conclusion

Table 12 shows the summary and recommendations for the event scenarios examined, given the risk reduction obtained by subtracting the event scenario initiating frequency from the value of the mitigated consequence. Table 13 shows the key findings of this paper, the comparison of posterior values to the prior and likelihood information.

The use of Bayesian-LOPA methodology for SGCS risk evaluation in this paper was proven to be a useful method of analysing risks that may occur in SGCS operations. HAZOP study however is needed for the adequate application of the methodology. The HAZOP study helps to streamline the risks foregrounding those with potentially major consequences for the immediate environment and the system at large. The event scenarios that could lead to a major disaster were considered under LOPA by combining SGCS specific data and generic data as likelihood and prior information.

Although LOPA is mainly used in chemical processes, SGCS is related to such a process due to the similarities of its unit operations. Therefore, the use of LOPA is justified. Failure data is crucial in the use of LOPA for the computation of risk frequencies. However, failure data from SGCS is limited due to its novelty and limited experimental data history. This shortcoming is addressed through Bayesian logic due to its ability to update either SGCS data or data from a similar industry with generic data. In other words, Bayesian logic tends to give a refined solution for LOPA utilisation by striking a balance between short term and long term data. The results from applying this method to some events and scenarios gave an overview of the potential consequences of an initiating event with respect to the risk values. Recommendations for additional SIS to meet an appropriate SIL were provided. HAZOP information is vital for LOPA. Even through subsea operations mainly use HAZID and FMEA, it can be easily mapped into HAZOP. Initiating events, failure frequencies and IPLs' PFDs were evaluated with Bayesian logic. The methodology gave the quantified risk results of the event scenarios which were made clearer with a LOPA event tree diagram. The outcomes were compared with the tolerable risk criteria given by CCPS as a benchmark. Further decisions were made to increase the SIS in order to meet the desired SIL after comparison in order to improve the safety procedures of SGCS and further research into its associated risks and risk reduction.

Conjugate gamma distribution produced the values for initiating event frequencies used for prior information, while Poisson distribution produced the values for the likelihood function, both of which were balanced by Bayesian logic to produce posterior values. The OREDA database with gamma distribution values was used for the prior information. The Jeffery's non-informative prior however can be used if there is no prior information. This was shown by the lack of information in one of the event scenarios. Data from available literature was used in the derivation of SGCS specific likelihood data. The IPLs' PFDs were evaluated under binomial likelihood distribution and conjugate beta prior distribution. The provision of failure frequency data in the beta distribution format made the use of the EIReDA database suitable for prior information. The frequency-PFD converter developed by Yun was used to generate failure frequency data where EIReDA did not give their values. The amalgamation of Bayesian logic and LOPA produces the Bayesian-LOPA methodology. The posterior values derived from the Bayesian-LOPA methodology are safer and more reliable to use in modelling an event scenario when compared to expert judgements, generic data, values from literature reviews and experimental data; in this case the likelihood and prior information. Thus, an improved judgement can be made in the application of a safety instrumented system (SIS) for a required safety integrity level (SIL).

Conflict of Interest

The authors have no conflict of interest to declare.

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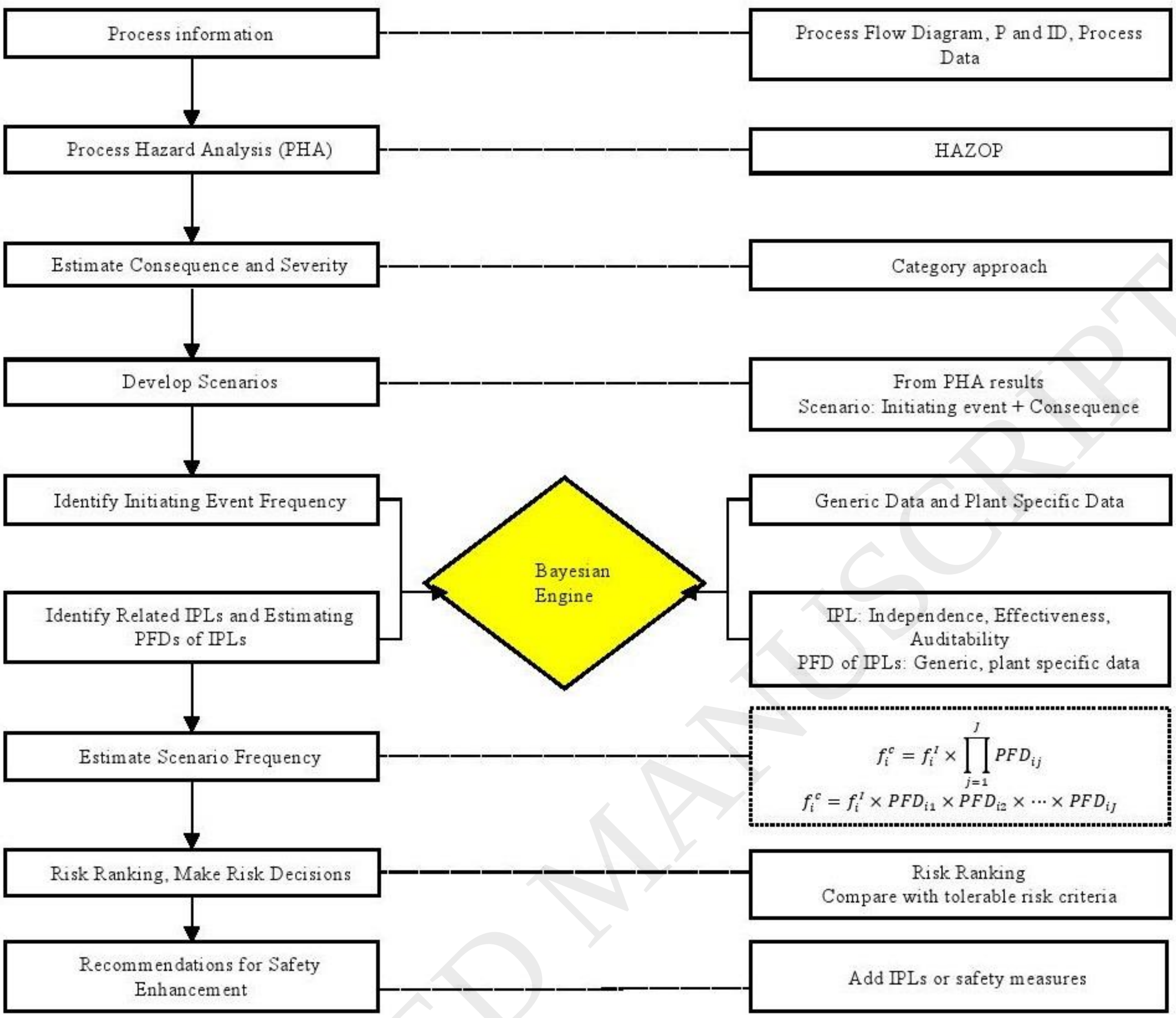


Figure 1: Research flow diagram (Adapted from Yun [31])

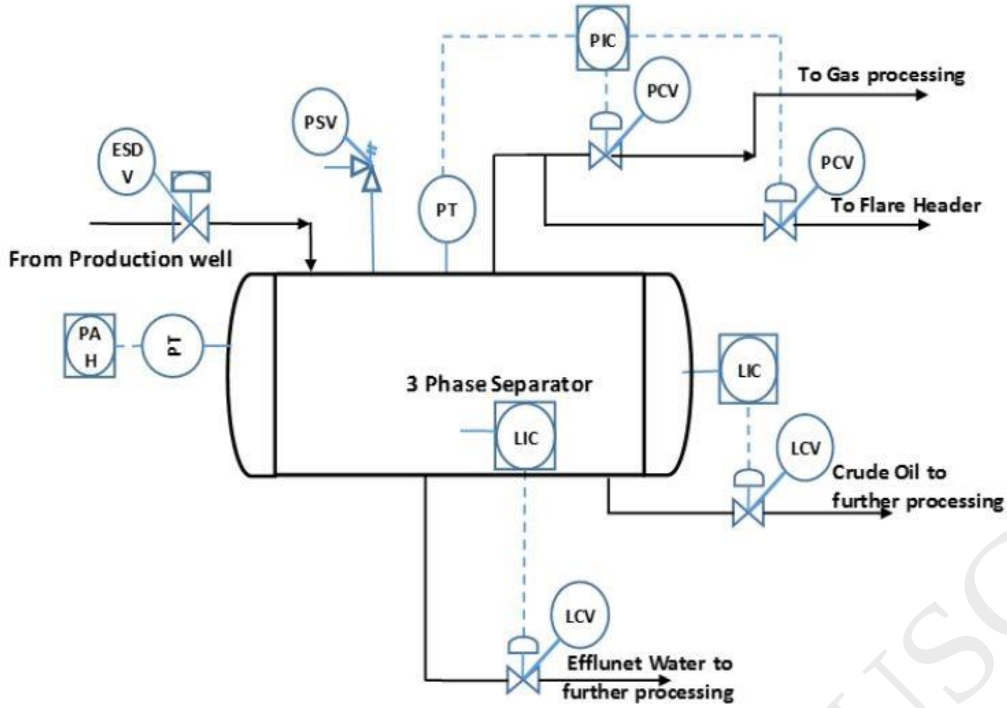
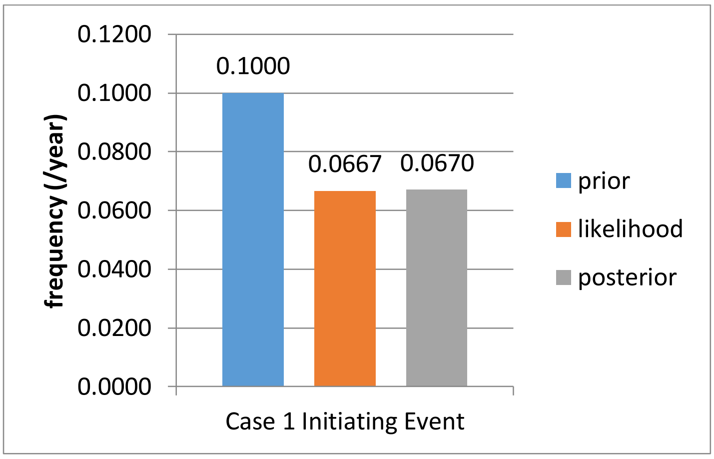
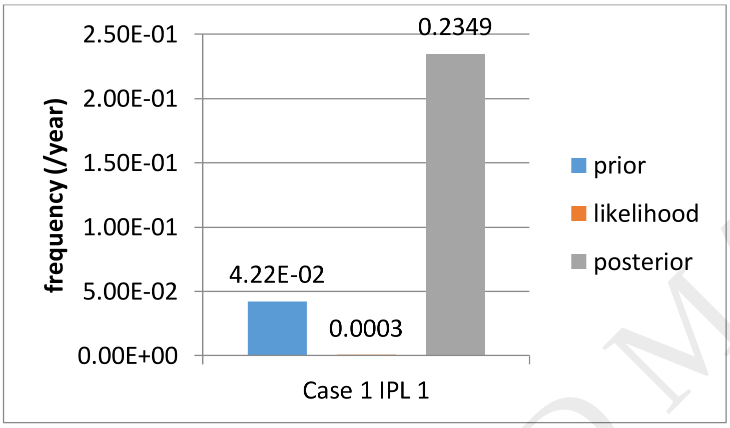


Figure 2: Gas-Liquid Separator showing Layers of Protection [38]

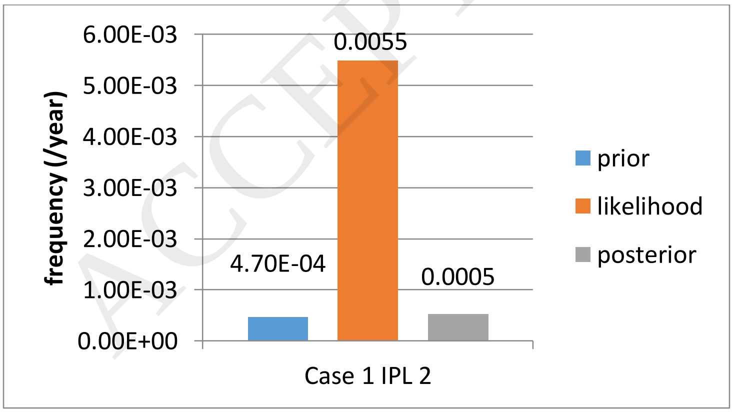
a)


0.1200
0.1000
0.0800
0.0600
0.0400
0.0200
0.0000
frequency (/year)
0.1000
0.0667
0.0670
prior
likelihood
posterior
Case 1 Initiating Event

b)


2.50E-01
2.00E-01
1.50E-01
1.00E-01
5.00E-02
0.00E+00
frequency (/year)
0.2349
4.22E-02
0.0003
prior
likelihood
posterior
Case 1 IPL 1

c)


6.00E-03
5.00E-03
4.00E-03
3.00E-03
2.00E-03
1.00E-03
0.00E+00
frequency (/year)
0.0055
4.70E-04
0.0005
prior
likelihood
posterior
Case 1 IPL 2

d)

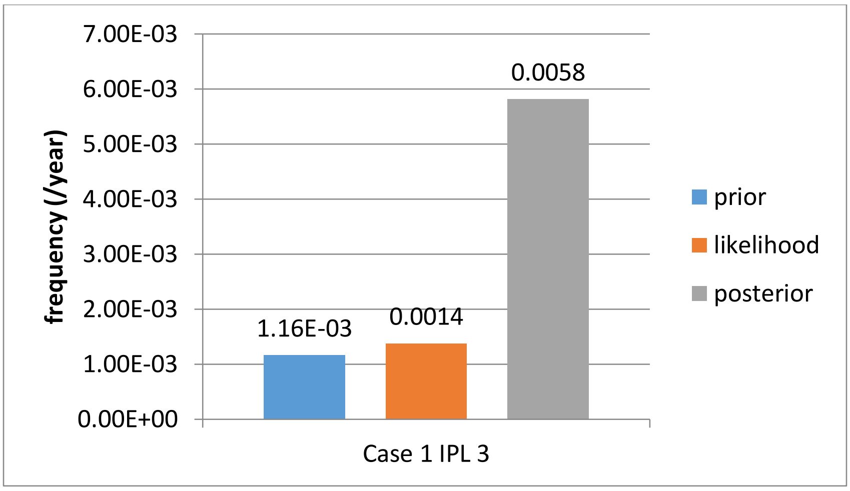


Fig.3: (a) Frequency of pressure increase updated with Bayesian logic, (b) Pressure alarm PFDs updated with Bayesian logic, (c) Pressure control valve PFDs updated with Bayesian logic, (d) Emergency shutdown valve PFDs updated with Bayesian logic

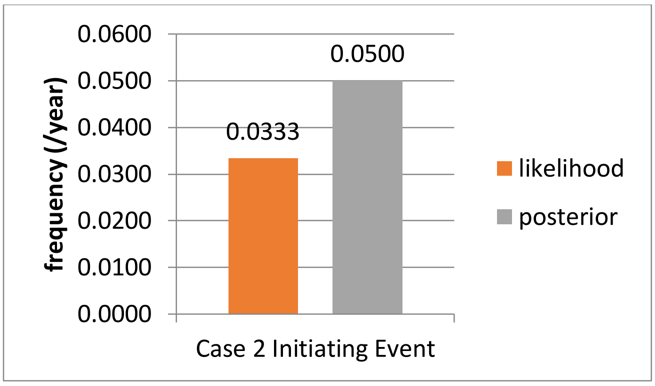
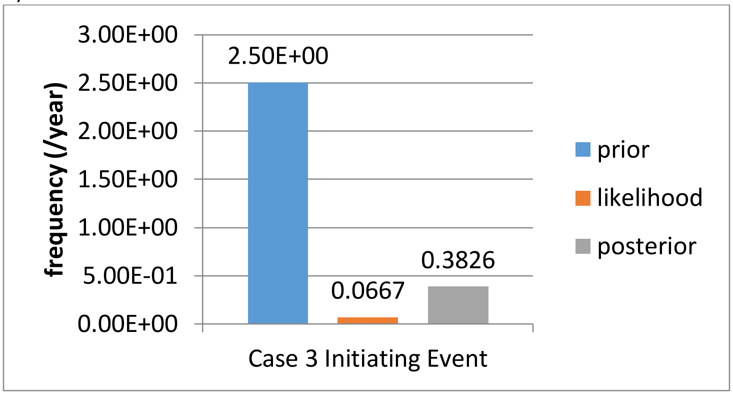
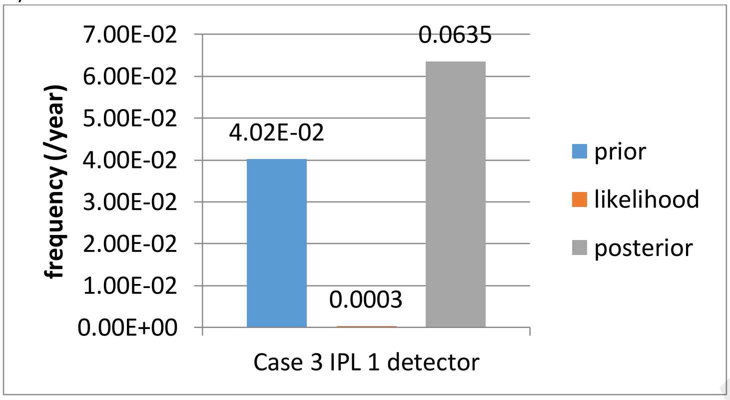


Fig.4: Frequency of human errors updated with Bayesian logic

a)



b)



c)

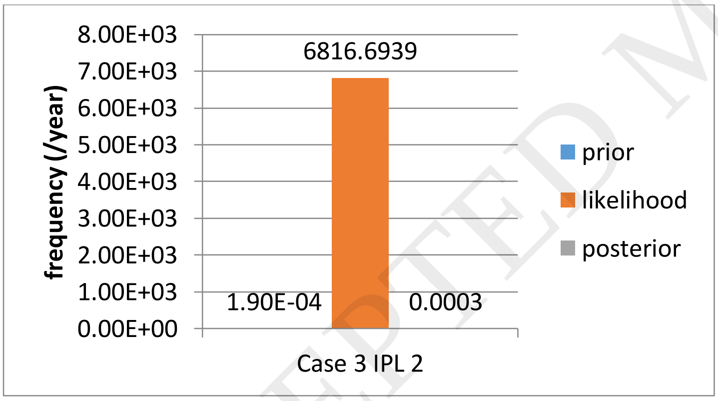


Fig.5 (a): Frequency of pump failure updated with Bayesian logic, (b) Frequency of level detector updated with Bayesian logic and (c) Frequency of backup pump failure updated with Bayesian logic

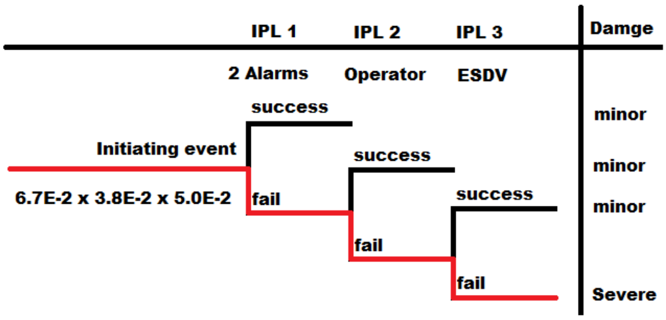


Fig.6: LOPA event tree following the event of case 4

Table 1: Databases and associated industrial applications

Database	Source	Application	Remarks
ESReDA/ EIReDA	European Safety and Reliability Research and Development Association/ European Industry Reliability Data Bank	Electricite de France	The data offers, distribution values, average values of PFD and frequencies etc. α and β factors were provided for gamma distribution which was used for failure frequency. For PFD beta distribution α and β were also provided [16]. The database is used to generate data for prior distribution.
DNV-GL (DNV-GL 2015)	Det Norske Veritas and Germanischer Lloyd	Oil and gas sector	Data collated from this organisation are focused on offshore classification, risk management; marine assurance etc. and its uses are referenced appropriately. [17, 18, 19]
OREDA	The Offshore Reliability Data	Offshore platform installations	The values are used as part of the data for the prior distribution in the Bayesian estimation for PFDs of IPLs and initiating frequencies. [20]
CCPS	The Centre for Chemical Process Safety	Reliability analysis of process equipment	It gives the PFDs and values of lower, mean and upper failure frequencies [21, 22].
IEC 61508/ IEC 61511	International Electro-Technical Commission	Safety integrity level (SIL) and probability of failure on demand (PFD)	IEC provides PFDs values with regards to personnel safety hence the use of SIL instead of environmental integrity level (EIL) in the case of SGCS it is not differentiated [23, 24, 25].

Table 2: Asgard SGCS unit operation components and specifications [4, 26]

Characteristics	**Value**
Design Life	30 Years
Water Depth	250 – 325 m
Design Gas Flow	25 MSm^3/d
Design pressure	210 bar
Max LVF into compressor	0.46
Number Trains	2 + 1 spare
Compressor power	2 x 11.5 MW
Structure Size	75 m x 45 m x 20 m
Weight	4800 tons
Compressor type	2 x integrated motor centrifugal compressor
Number Pumps	2 x centrifugal pumps
No of coolers	2 anti-surge + 2 passive coolers
Separators	Two-phase vertical separators X 2

Table 3: Safety Integrity Level with tolerable risk criteria for Probability of Failure on Demand Average

SIL	PFD_{avg}	Reduced Risk
1	$\geq 10^{-2}$ to 10^{-1}	>10 to ≤ 100
2	$\geq 10^{-3}$ to 10^{-2}	>100 to ≤ 1000
3	$\geq 10^{-4}$ to 10^{-3}	>1000 to ≤ 10000
4	$\geq 10^{-5}$ to 10^{-4}	>10000 to ≤ 100000

(Adapted from IEC [25])

Table 4: Category of consequences and tolerable frequencies

Category	Tolerable frequency
Multiple fatalities of personnel	$1*10^{-6}$
The environment	$1*10^{-4}$
Facility (Assets)	$1*10^{-4}$

[Adapted from Unnikrishnan et al [38]]

Table 5: Customized table showing FMEA adapted for HAZOP in SGCS

Event Scenario	Guideword/ severity	Process Parameter	Deviation/ failure mode	Failure Causes	Consequences	Layers of Protections/ risk reducing measure
Gas Liquid Separator	High/ Major	Pressure	Pressure exceeding design pressure	External Influence from within the reservoir, Human errors operator fails to balance pressure	Release of containment	Alarm, operator's response to initiate PCV, emergency shutdown procedure
Multiphase Pump	Severe/ critical	Temperature	Loss of head and pressure	Pump failure	SGSC damage which leads to high maintenance cost etc.	Equipment failure detector and alarm, backup equipment, emergency shutdown procedure

Table 6: Customized table showing LOPA event scenarios

Event Scenario Nos.	Causes	Consequences	Event Scenarios
1	External influence	Release of containment	Case 1
2	Operator's error	release of containment	Case 2
3	Device Failure	SGCS damage	Case 3

Table 7: Customized table showing initiating events frequencies

Class	Prior data					Likelihood data		
Event	Minimum	Mean (per year)	maximum	Standard Deviation	Note and References	Operating years	Number of failures	Note and References
Increase in pressure	0	0.1	0	0.9985	OREDA	30	2	CCPS [21, 22] and Asgard SGCS [40]
Human errors	-	-	-	-	-	30	1	CCPS & Expert Judgement
Pump failure	0	2.50	3.90	3.2384	OREDA & DNV	6	1	Dash [41]

Table 8: Customized table showing probability of failure on demand of IPLs

Class	Prior Data										Likelihood data			
Event	Alpha	Beta	Lower PFD	Mean PFD	Upper PFD	Lower (/year)	Mean (/year)	Upper (/year)	S.D.	References	Nos. of failure	MTBF (year)	Test Interval (year)	References
PAH	-	-	-	-	-	1.73×10^{-4}	4.22×10^{-2}	1.62×10^{-1}	5.96×10^{-2}	OREDA	2	1.52×10^{2}	0.0833	CCPS [21, 22] & expert judgement
PCV	2.90×10^{1}	6.20×10^{4}	3.00×10^{-4}	4.70×10^{-4}	6.00×10^{-4}	-	-	-	-	EIReDA	4	1.82×10^{2}	2.0000	CCPS [21, 22]
ESDV	4.97×10^{0}	4.29×10^{3}	7.20×10^{-4}	1.16×10^{-3}	1.56×10^{-3}	-	-	-	-	EIReDA	20	3.03×10^{1}	0.0833	CCPS [21, 22]
LAH	-	-	-	-		1.28×10^{-2}	4.02×10^{-2}	8.00×10^{-2}	2.11×10^{-2}	OREDA	2	1.52×10^{2}	0.0833	CCPS & Christopher [42]
LP, HP pump	8.80×10^{0}	4.41×10^{4}	1.10×10^{-4}	1.90×10^{-4}	2.70×10^{-4}	-	-	-	-	EIReDA	6	6.11×10^{-6}	0.0833	CCPS & Dash research

Table 9: Case 1 LOPA spread sheet

Event scenario	Case 1 Posterior (Bayesian Logic)		
Date	Description	Probability	Frequency (/year)
Consequence Description/ Category			
Risk Tolerance Criteria (Frequency)			> 1.00E-3 < 1.00E-5
Initiating event (Frequency)	Increase in pressure within the separator due to pressure surge from the reservoir		6.70E-02
Frequency of Unmitigated consequence			6.70E-02
Independent Protection Layers	Pressure Alarm (PAH)	2.40E-01	
	Pressure control valve(PCV)	5.00E-04	
	Emergency shutdown Valve (ESDV)	5.80E-03	
Total PFD for all IPLs		6.81E-07	
Frequency of Mitigated Consequence (/year)			4.50E-08
	YES		
Actions Required to meet Risk Tolerance Criteria	There should be 1-month test intervals for the pressure alarm. An independent logic solver should be put in place to give maximum credit points in case a particular IPL has two devices		
Notes			
References			

Table 10: Case 2 LOPA spread sheet

Event scenario	Case 1 Posterior (Bayesian Logic)		
Date	Description	Probability	Frequency (/year)
Consequence Description/ Category			
Risk Tolerance Criteria (Frequency)			> 1.00E-3 < 1.00E-5
Initiating event (Frequency)	Increase in pressure within the separator due to pressure surge from the reservoir		6.70E-02
Frequency of Unmitigated consequence			6.70E-02
Independent Protection Layers	Pressure Alarm (PAH)	2.40E-01	
	Pressure control valve(PCV)	5.00E-04	
	Emergency shutdown Valve (ESDV)	5.80E-03	
Total PFD for all IPLs		6.81E-07	
Frequency of Mitigated Consequence (/year)			4.50E-08
Risk Tolerance Criteria Met? (Yes/No)	YES		
Actions Required to meet Risk Tolerance Criteria	There should be 1-month test intervals for the pressure alarm. An independent logic solver should be put in place to give maximum credit points in case a particular IPL has two devices		
Notes			

Table 11: Case 3 LOPA Spread Sheet

Event scenario	Case 3 Posterior (Bayesian Logic)		
Date	Description	Probability	Frequency (/year)
Consequence Description/ Category			
Risk Tolerance Criteria (Frequency)			> 1.00E-3 < 1.00E-5
Initiating event (Frequency)	Human errors operator fails to alert system to balance pressure		3.80E-01
Frequency of Unmitigated consequence			3.80E-01
Independent Protection Layers	Level Detector (LAH) Pressure Alarm (PAH)	2.80E-01	
	Backup Pump	3.00E-04	
	Emergency shutdown Valve (ESDV)	5.80E-03	
Total PFD for all IPLs		4.93E-07	
Frequency of Mitigated Consequence (/year)			1.90E-07
Risk Tolerance Criteria Met? (Yes/No)	YES		
Actions Required to meet Risk Tolerance Criteria	There should be drills for operators to check their readiness for such an event scenario. Detectors and alarms should be independent of operator's in other to maintain risk value SIS for SIL 4 should be considered		

Table 12: Risk reduction summary of event scenarios

Event scenario	Failure frequency (/year)	Criteria Met	SIL nos.	Risk reduction	Recommendations
Case 1	6.70E-02	YES	-	0.0670	An independent logic solver should be put in place to give maximum credit points in case a particular IPL has two devices
Case 2	5.00E-02	YES	-	0.0410	There should be drills for operators to check their readiness for such an event scenario.
Case 3	3.80E-01	YES	-	0.3710	SIS for SIL 4 should be considered

Table 13: Comparison of Values

	Prior	Likelihood	Posterior
Case 1 IE	1.00E-1	6.67E-2	6.70E-2
Case 1 IPL1	4.22E-2	3.00E-4	2.35E02
Case 1 IPL2	4.70E-4	5.50E-3	5.00E-4
Case 1 IPL3	1.16E-3	1.40E-3	5.80E-3
Case 2 IE	-	3.33E-2	5.00E-2
Case 3 IE	2.50E+0	1.67E-1	3.83E-1
Case 3 IPL1	4.02E-2	3.00E-4	6.35E-2